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The future of frequency response in Great Britain

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Abstract

Electricity grids around the world are rapidly changing to accommodate an increasing penetration of renewable generation. Grid ancillary services, such as frequency response, are important tools an electricity system operator has at their disposal for maintaining grid stability. In Great Britain, the electricity system operator recently proposed new frequency response services (dynamic regulation, dynamic moderation, dynamic containment, and static containment) designed for the future needs of the system. Here we analyse the efficacy of these new services using a month-long case study and use the current services as a comparison. We calculate that the total frequency response capacity needed is 450 MW of high response (needed when $\Delta f > 0$) and 550 MW of low response (needed when $\Delta f < 0$), including 150 MW of dynamic regulation and 150 MW of dynamic moderation to reproduce frequency volatility levels seen currently. We also investigate how the new services perform in a future reduced inertia scenario, developed using National Grid ESO's Future Energy Scenarios. The inertia in this future scenario is provided by nuclear and demand only and has a median value 5 times smaller than current values. We find that the new services can successfully mitigate against the reduced inertia with a 50 MW addition of capacity to dynamic regulation.

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Keywords: Grid stability; Frequency events; Frequency response; Renewable penetration

1. Introduction

Maintaining a stable grid is one of the top priorities of electricity system operators (ESOs) [1,2]. To achieve this, the ESO must ensure a second-by-second balance of generation and demand. The AC frequency of the grid, the frequency at which all synchronously connected generators and demand units rotate at, is a measure for how well this balance is realised. When generation is greater than demand, the frequency rises and vice versa. Thus, ESOs maintain a frequency as close to the nominal value as possible, which is 50 Hz in GB. In GB, the operational limits for frequency are ±0.2 Hz and the statutory limits are ±0.5 Hz.

Frequency response (FR) services are the tool that ESOs use for second-by-second balancing of the grid. FR is provided by generation and demand units that can alter their power input or output in response to changes in the

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Table 1. The characteristics and aims of current GB frequency response services.

FR service	Speed	Duration	Aim
Primary	Within 10 s	30 s	To contain a falling frequency when f < 50 Hz
Secondary	Within 30 s	30 min	To restore frequency back to 50 Hz when f < 50 Hz
High	Within 10 s	Continuous	To contain and restore frequency back to 50 Hz when f > 50 Hz
Enhanced	Within 1 s	15 min	To provide fast response either side of 50 Hz (symmetric service)

grid frequency. FR, along with voltage regulation, reserve, and system restoration is an important ancillary service which is necessary in all large-scale grids around the world. Recently, GB's ESO has proposed a new suite of FR services [3], which over the coming years will replace the current suite. This change has been prompted by growing concern that the current services are not fit for a future reduced inertia grid with a higher penetration of wind and solar. The rate of change of frequency (RoCoF) after an imbalance between generation and demand is inversely proportional to the amount of inertia on the grid, so inertia is therefore a stabilising property. Wind and solar are inherently intermittent forms of generation and decrease the level of inertia of a grid as their penetration levels increase. GB's ESO has an ambition to run a zero-carbon grid, for short periods of time, by 2025 [4], and these new FR services are designed with this goal in mind and also designed to be technology neutral.

Previous work on frequency volatility and reduced inertia in power systems has focused primarily on single large infeed loss events [5]. It has been found that FR needs to be faster acting (within 1 s) as inertia levels decrease. There have also been a few studies on longer-term frequency volatility [6] and the ideal technology choice for specific FR services [7]. Johnson et al. [8] used unit commitment and dispatch modelling to quantify the amount of inertia in the Texas grid in future scenarios and in a later publication [9] the authors investigated the feasibility of extremely high penetrations of renewables and identified mitigation pathways. They found that low inertia could prevent a 100% penetration of renewable generation.

The relationship between frequency response, grid inertia, and frequency volatility has been covered by the existing literature. However, there are no studies on the proposed new frequency response services and their effect on frequency volatility. To fill this gap in knowledge and to further existing work, this paper addresses the following research questions:

- What is the efficacy of the proposed new FR services compared with the existing frequency response services?
- How do the proposed new FR services deal with a future reduced inertia scenario?

To address the first question, we model the GB grid (based on the swing equation [10]) and the different FR services. We run month-long simulations and compare the frequency volatility for different FR mixes. We address the second question by creating two different inertia scenarios (current and future) and again running month-long simulations. The two inertia scenarios are created using historical data and predictions by the GB ESO.

The remainder of this paper is structured as follows. Section 2 explains the characteristics and aims of the current and proposed new FR services in GB. Section 3 guides readers through the methodology. Section 4 presents the results and discussion that address the research questions. Section 5 provides conclusions.

2. Current and proposed new frequency response services

In GB, there are 4 main types of FR service. Their characteristics and aims are presented in Table 1. Primary, secondary, and high FR are either dynamic or static: dynamic FR is the continuous provision of proportional response as the frequency changes, and static FR is a discrete service activated when the frequency passes a defined value. Enhanced FR (EFR) is a relatively new dynamic service, which is much faster acting than the other dynamic services. In 2016, GB's ESO procured 200MW of EFR via a tender exercise [11], and all of the contracts were awarded to batteries. By summer 2018, all contracts were delivering their contracted volume.

The dynamic services are all modelled with the following relationship between required FR power output and frequency deviation (power–frequency relationship): a deadband (the period either side of 50 Hz during which a service is not delivered) of ±0.015 Hz, a linear increase outside of the deadband, and a maximum output at a ±0.5 Hz deviation. This is to match the definition of primary, secondary, and high FR capability values found in the GB Grid Code [12] and EFR delivery envelope [11].

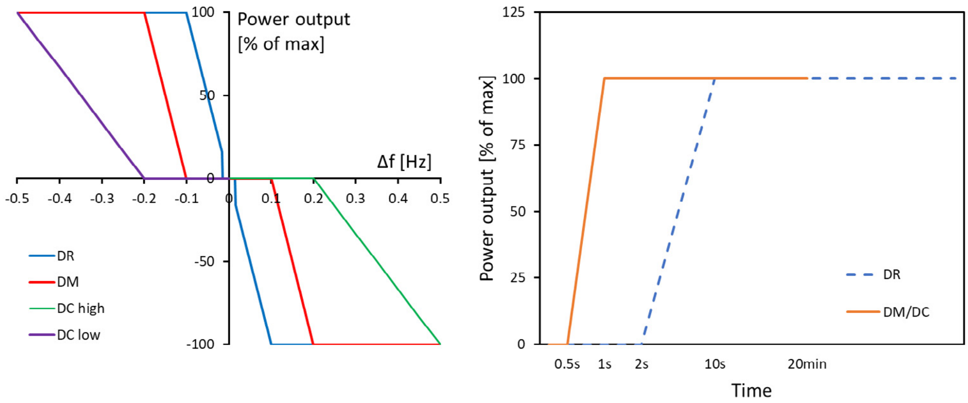

Fig. 1. The characteristics of proposed new frequency response services: the power–frequency relationship (left) and delay, ramp, and duration times (right).

Recently, GB's ESO proposed new FR services designed to be better suited to future system needs. The 4 new FR services proposed are called dynamic regulation (DR), dynamic moderation (DM), dynamic containment (DC), and static containment (SC), which we do not consider in this paper. DR and DM are symmetrical services, so providing 1 MW of the service means providing 1 MW of upwards (low) response and 1 MW of downwards (high) response. DC is not a symmetrical service: a provider can choose to provide either upwards (DC low) or downwards (DC high) response or both.

The characteristics of the new FR services (except SC) are detailed in a publication by GB's ESO [3] and can be seen in Fig. 1. On the left of Fig. 1 is the relationship between required FR power output and frequency deviation for each service and on the right is the response and duration time required for each service. DR has a deadband of ±0.015 Hz and is at maximum output at ±0.1 Hz. Providers of this service must respond within 2 s of a frequency deviation outside the deadband and be able to ramp up to maximum output within 10 s. The provider must also be able to respond continuously, which in other words means having an infinite duration. DM starts at ±0.1 Hz and is at maximum output at ±0.2 Hz. Note the slight difference in response between DR and DM just outside their respective deadbands. DM has a maximum delay time of 0.5 s and full output must be reached within 1 s. The service must be sustained for at least 20 min. The purpose of DM is to occasionally assist DR by providing rapid response when frequency deviations start becoming slightly concerning. DC high and low start at ±0.2 Hz, the operational limits of frequency deviation in GB. DC has a maximum output at ±0.5 Hz and must have the same rapid response as DM and the same duration. DC is expected to be used very infrequently for large, unexpected frequency deviations to prevent the statutory limit of ±0.5 Hz being breached.

3. Methodology

This was shortened and adapted from [13].

3.1. GB grid model

The GB grid model used in this study is based on the swing equation:

$$df/dt = f_n^2(R + I - kD_n\Delta f)/2E_n f.$$

f_n [Hz] is the nominal frequency of the grid and $\Delta f = f - f_n$. E_n [MW.s] is the total rotational kinetic energy stored in the grid at f_n, which is what we define as inertia in this paper. R [MW] is the FR of the grid, which can be positive or negative. I [MW] is the power imbalance of the grid and is positive when generation is greater than demand and negative when demand is greater than generation. D_n[MW] is the demand of the grid at f_n and k is the demand damping constant, set to 0.02 in this paper.

Fig. 2 shows how the swing equation can be used to calculate the imbalance of the grid, which there is no raw data for. Half-hourly generation data [14,15] and inertia constants [16] are used to calculate the half-hourly inertia

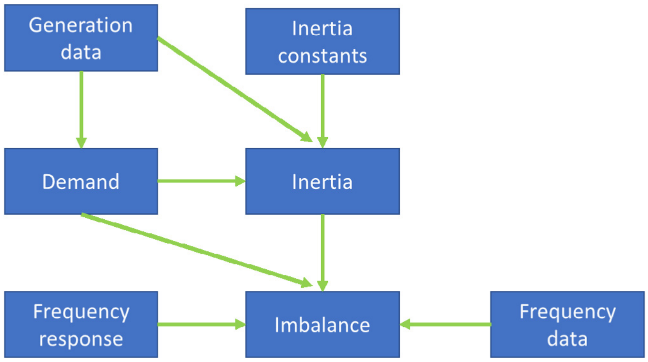

Fig. 2. The method for calculating the imbalance of the grid using the swing equation.

profile of the grid. The generation data is also used to calculate the demand. Frequency response is modelled based on the characteristics described in Section 2. Primary and secondary response are combined into a single service: low frequency response (LFR). All of the above, along with 1 s resolution frequency data, is used in a rearranged swing equation to calculate the imbalance of the grid. The imbalance can be estimated at 1 s resolution by linearly interpolating the half-hourly data.

3.2. November 2018 case study

November 2018 (Nov 18) is chosen as a case study month due to it being a recent month where the frequency does not deviate outside of ±0.3 Hz. This allows us to ignore static frequency response, which activates at this deviation. In Nov 18, there were 239 (134 high and 105 low) frequency events. The maximum frequency during the month was 50.291 Hz, the lowest was 49.701 Hz, and the standard deviation was 0.070 Hz.

First, the imbalance of Nov 18 was calculated using the method shown in Fig. 2. Capacities of primary and secondary frequency response (combined as LFR), and high frequency response (HFR) were obtained from an ESO market report for Nov 18 [17]. The imbalance profile was then used in subsequent simulations, with FR capacities varied, to calculate the frequency during the month.

3.3. Future reduced inertia scenario

We predicted an inertia profile for November 2030 (Nov 30) by using National Grid ESO's Future Energy Scenarios (FES). We took the Community Renewables scenario and scaled the Nov 18 nuclear based on the expected capacity decrease of this form of generation. We then assumed that only nuclear and demand provides inertia in Nov 30. This is an extreme scenario, but entirely possible if wind and solar capacity increases to the level predicted in the FES. Fig. 3 shows the duration curves of the Nov 18 and predicted Nov 30 inertia profile. The median of the Nov 18 profile is 298 GW.s and the median of the Nov 30 profile is 66 GW.s, a 5-fold decrease.

4. Results and discussion

4.1. Definitions

These definitions are necessary for understanding the results that follow in the next section.

- Idle time: the amount of time the FR service has zero output as a percentage of the total time
- Utilisation: the mean of the absolute output of the FR service (excluding idle time) as a percentage of the power capacity
- Delivery volume: the energy flow of the FR service (positive for output into grid and negative for the reverse)
- High frequency event: when the frequency goes above 50.2 Hz (upper operational limit) for any length of time
- Low frequency event: when the frequency goes below 49.8 Hz (lower operational limit) for any length of time

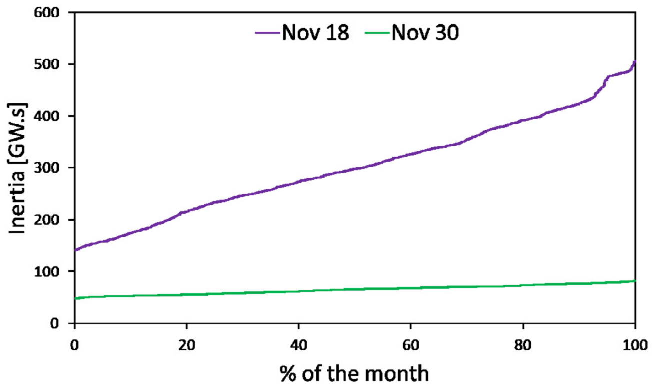

Fig. 3. Duration curves of the November 2018 and predicted November 2030 inertia profiles.

Table 2. Idle time, utilisation, and delivery volume of each current frequency response service during the November 2018 simulation.

Current FR service	Capacity [MW]	Idle time	Utilisation	Delivery volume [MWhs]
Low	500/600/800	0.55	0.13	26 000
High	200	0.57	0.13	−8100
Enhanced	200	0.13	0.13	8300/-8100

4.2. Frequency response in current inertia scenario

In this section we perform month-long simulations with the Nov 18 imbalance and Nov 18 inertia profile. Running the simulation with the current FR services with the same capacities specified in Section 3 (ESO market report [17]) produces the exact same Nov 18 frequency volatility detailed in that section. Table 2 shows the capacity, idle time, utilisation, and delivery volume of each current FR service in the same simulation. LFR and HFR spend more time being idle than EFR since they only respond in one direction. All services have the same utilisation because the frequency distribution is very close to symmetric and they all have the same power–frequency relationship. However, the frequency distribution is not exactly symmetric as evidenced by the fact that EFR outputs slightly more power than takes in.

Fig. 4 shows the results of simulations in which the proposed new FR services were providing the FR during the month. In all cases (in both the left and right plot) the total FR capacity is 450 MW on the high side and 550 MW on the low side. In the left plot, the capacity of the sum of DM and DR was varied (in every case DM = DR). DC fulfils the rest of the capacity up to 450/550 MW. The number of events (high + low) decreases as DM+DR increases, as expected. Above DR = DM = 150 MW, the number of events is below the Nov 18 value of 239. In the right plot, the capacity of DR was varied and DR+DM kept constant at 300 MW, again DC fulfils the rest of the capacity up to 450/550 MW. The standard deviation of frequency decreases as DR capacity increases, improving on the Nov 18 value at DR = 150 MW and above.

Table 3 shows the idle time, utilisation, and delivery volume of each proposed new FR service at a capacity mix that gives similar frequency volatility to Nov 18. DR has a similar idle time to EFR, but a much higher utilisation due to having maximum output at ±0.1 Hz rather than at ±0.5 Hz. DM is idle for 89% of the time and has a 27% utilisation. DC high and low are both active for less than 0.5% of the time. As can be seen from the delivery volumes, DR is doing the bulk of the work, with DM offering occasional assistance and DC offering rare assistance. There is a large disparity in delivery volume between input and output for the DM service. This service could be provided by batteries due to the fast response required. However, the battery would lose state-of-charge throughout the month and would need a state-of-charge balancing strategy to avoid needing a prohibitively large energy capacity.

To summarise, the DR capacity alone is the main factor influencing standard deviation and the sum of DR and DM capacity is the main factor influencing the number of frequency events. The DC capacity has an insignificant influence on both of these measures of frequency volatility due to its large deadband of ±0.2 Hz. However, DC

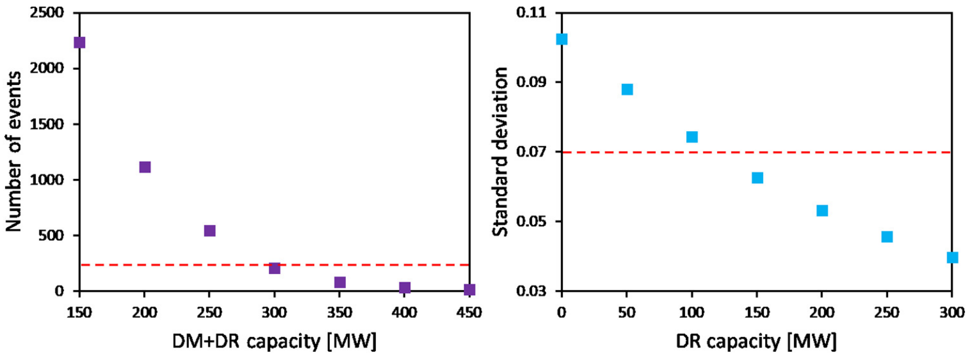

Fig. 4. The number of frequency events (high + low) during the month for different combined capacities of dynamic regulation and moderation (left) and the standard deviation of frequency during the month for different dynamic regulation capacities (right). The red dashed lines indicate the real November 2018 values.

Table 3. Idle time, utilisation, and delivery volume of each proposed new frequency response service (at a specific capacity mix) during November 2018 simulation.

Current FR service	Capacity [MW]	Idle time	Utilisation	Delivery volume [MWhs]
DR	150	0.14	0.55	30 000/-21 000
DM	150	0.89	0.27	2900/-260
DC high	150	1.00	0.01	0
DC low	250	1.00	0.10	35

Table 4. Frequency volatility results for the proposed new frequency response services with a November 2018 inertia profile and a November 2030 reduced inertia profile. The DR, DM, and DC capacities are the same as in Table 3.

Inertia	Number of events	Standard deviation [Hz]	Max f [Hz]	Min f [Hz]
Nov 18	208	0.063	50.205	49.614
Nov 30	735	0.064	50.372	49.599

is extremely important to protect the grid when there are rare, large imbalances that DR and DM cannot contain alone.

4.3. Frequency response in future reduced inertia scenario

In this section we perform month-long simulations with the Nov 18 imbalance and Nov 30 reduced inertia profile. Table 4 shows the frequency volatility results, including the results from running the simulation with a Nov 18 inertia profile for comparison. For both simulations, the DR, DM, and DC capacities are the same as in Table 3. The reduced inertia causes an increase in the number of events by a factor of 3.5 but only a small increase in the standard deviation. The maximum frequency deviation reached during the month increases quite a lot on the high side with Nov 30 inertia but not so much on the low side. It was found that adding just 50 MW of extra capacity to DR (to 200 MW in total), reduced the number of events to 266 and the standard deviation to 0.055 Hz (similar, if not better, frequency volatility to Nov 18).

5. Conclusions

A summary of the key findings:

- DR capacity is the main factor influencing the frequency standard deviation and the sum of DR and DM capacity is the main factor influencing the number of frequency events
- 150 MW of DR and DM keeps standard deviation and the number of frequency events to acceptable levels

- The amount of DC capacity will depend on the future largest infeed loss. There must be enough DR+DM+DC to protect the grid against it.
- In a future reduced inertia scenario, an additional 50 MW of DR capacity can maintain the frequency volatility at current levels

It seems that the proposed new FR services have much more distinct roles than the current services. DR maintains an acceptable standard deviation, DM works with DR to prevent too many frequency excursions outside of ±0.2 Hz, and DC is for protecting the grid against rare, large events.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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